

APPENDIX A. RADAR SYSTEM MODEL

This appendix has been included to provide a framework for the discussion in the body of this report and the remaining appendices; it covers some of the fundamentals regarding the operations of a Frequency Modulated Continuous Wave (FMCW) radar. The TRW Forward-Looking Automotive Radar (FLAR) used for this evaluation program operates on the FMCW principles outlined here. Much of the material in this appendix was taken from a two-day automotive radar course developed by ERIM for the National Highway Traffic Safety Administration.

This appendix contains the following information:

- Description of Radar Functions
- Components of a Radar System
- Object Reflections
- FMCW Radar Operating Principles

A.1 DESCRIPTION OF RADAR FUNCTIONS

The functions that a radar sensor provides to a larger system, whether it is collision avoidance or adaptive cruise control, can be broken down into three basic functions and two more advanced functions, as outlined below:

- Basic Functions:
 - **Detection:** determining whether or not an object is present in the vicinity of the radar sensor
 - **Ranging:** reporting the linear radial distance from the radar sensor to a detected object
 - **Relative Range Rate (aka Relative Radial Velocity):** reporting changes in range of detected objects as a function of time
- Advanced Functions:
 - **Positioning:** determining the location of an object with respect to the radar in terms of range and direction
 - **Tracking:** the ability to uniquely identify detected objects and maintain a time-history of their position (implemented as a control algorithm in the processor which may/may not affect actual radar operations-for example, antenna control)

The basic functions are provided by direct analysis of the radar return signals. The advanced functions require more complex processing which may require consideration of radar signal history or interfacing with electronics other than the radar itself.

The “detection” function is normally achieved by comparing the radar energy reflections captured by the receive antenna to some threshold level. When an object generates returns within the radar receiver which are sufficient in amplitude, the object is “detected” by the radar.

The “ranging” function is normally carried out by measuring the time delay corresponding to the elapsed time between the transmission of radar energy and reception of the radar energy reflected back by that object. FMCW radars, like the FLAR, use a modulation technique on the transmitted signal to determine the time delay.

The “relative range rate” function can be achieved by two different methods. The first and most direct is to measure the “Doppler” shift induced on the transmitted radar energy by the movement of the object off which the radar energy reflects. The Doppler shift causes the frequency of the transmitted

waveform to be shifted either up or down, depending upon the target’s movement. The second method is range differentiation, which uses the difference between two consecutive range measurements to determine the rate at which the range is changing. The FLAR uses the range differentiation method to calculate relative range rate.

The “positioning” function requires knowledge of the radar’s antenna beam pattern and the current direction in which the antenna is pointed. By scanning an antenna beam across a scene and correlating returns to the beam’s direction, the radar sensor can position the target with respect to the radar. The TRW FLAR uses a beam-switching mechanism to point the beam in three different directions. (Another method of positioning is the use of “Monopulse Radar” which is beyond the scope of this appendix.)

The “tracking” function is achieved by having the radar internal processing electronics identify and maintain a time-history of the location of objects detected in the scene.

Figure A-1 illustrates the role of a radar in an overall system like collision warning. The radar itself is a source of data input to the higher level system. From the radar developer perspective, the partition between the radar signal processing electronics and higher level system processing can be drawn in various locations, as indicated by the dotted line in Figure A-1.

With respect to the diagram in A- 1, this program evaluates the raw radar signal that connects the transmit/receive electronics to the signal processing electronics within the “Radar Sensor” box. To a lesser degree, the program also evaluates the TRW proprietary algorithms which define the signal processing performed on the raw radar signal.

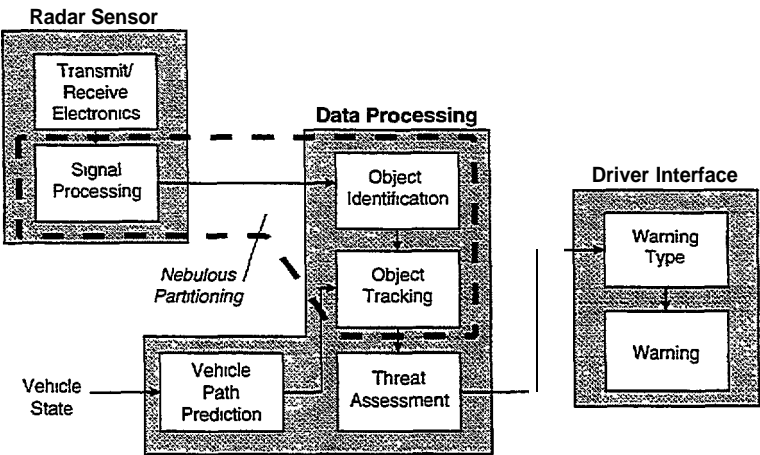


Figure A-1. Radar as Part of a Collision Warning System

A.2 COMPONENTS OF A RADAR SENSOR

Briefly, a radar is a device which emits electromagnetic energy (radio waves) and receives reflections of the emitted energy from objects within the radar’s field-of-view. The field of view is defined by the antenna pattern(s). In the case of the FLAR, the emitted energy is in the 94 GHz region.

Figure A-2 shows a block diagram of a “generic” radar sensor. Table A-1 lists the purpose for each of the components of the block diagram.

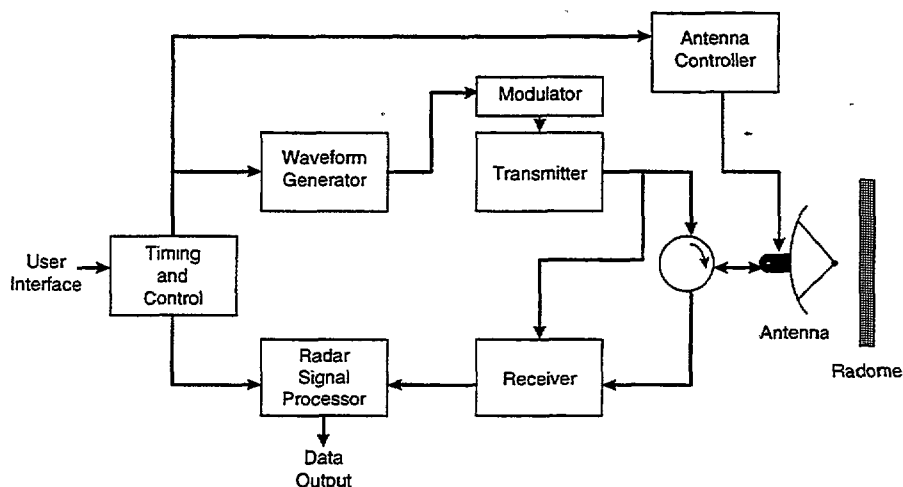


Figure A-2. A Generic Radar

Table A-1. Generic Radar Components

Component	Purpose
Waveform Generator	Controls the modulation of the transmitted waveform
Modulator	Controls the transmitter in terms of turning it on and off and dictating the frequency which is transmitted
Transmitter	Controls the power level of the emitted radio wave energy
Antenna/Controller	Concentrates and directs the emission of the radio energy
Receiver	Amplifies, filters, translates/demodulates the reflected energy, and formats it for use by the processing electronics
Signal Processor	Performs functions on the received signal to extract detection, range, and range rate info
Timing and Control	Synchronizes the operation of the other radar components

A.3 OBJECT REFLECTIONS

Different materials reflect radar energy to differing levels. Conductive surfaces such as metals reflect radar energy very well. Non-conductive surfaces reflect radar energy to varying degrees, based on their dielectric constant. Figure A-3 illustrates that when radar energy strikes an object, three things can happen: (1) the energy can be reflected, (2) the energy can be absorbed by the material, and (3) the energy can pass through the material. The degree to which any of these three possibilities occurs is dependent upon the dielectric constant, object geometry, and the angle at which the radar energy strikes the object (i.e., the incident angle).

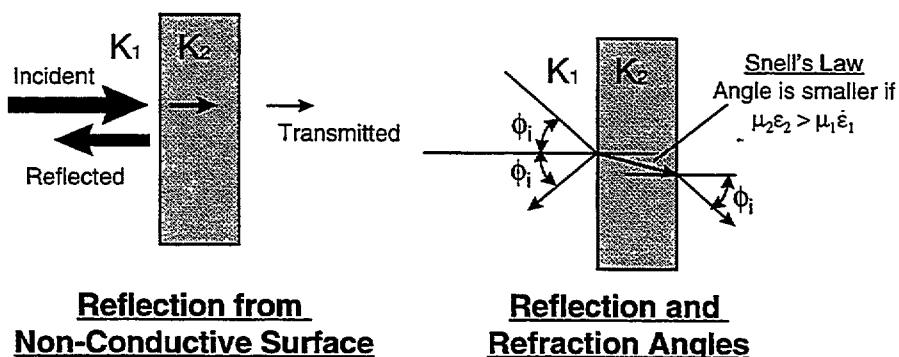


Figure A-3. Radar Energy Reflection and Refraction

Figure A-4 indicates what happens to the radar energy based on the incident angle. Reflection is similar to the optical reflection observed in a mirror. Refraction occurs when the radar energy gets “bent” as it passes through the interface between two mediums with different dielectric constants.

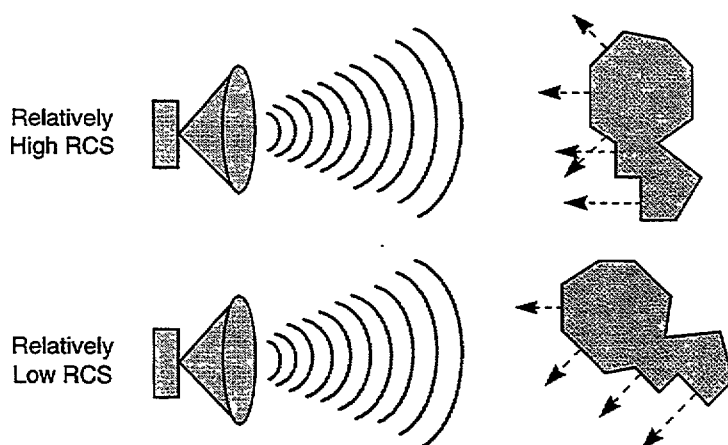


Figure A-4. Radar Returns and Orientation

Besides its material, the object’s orientation also dictates how much energy is reflected back toward the radar. Figure A-3 shows an object which in one orientation causes a large return in the radar, while in another orientation causes a relatively low level return in the radar.

The amount of energy reflected back toward a radar by a particular object at a given orientation with respect to the radar is quantified by a parameter known as “Radar Cross Section” (RCS). The formal definition for RCS is given by the equation:

$$\sigma = 4 * \pi * \frac{\text{Reflected power / Unit solid Angle}}{\text{Incident power / Unit area}}$$

RCS is typically measured in square meters or the decibel equivalent “dBsm,” which is referenced to 1 square meter.

A more intuitive definition for RCS is illustrated in Figure A-5. Shown are two similar theoretical test setups. The first setup shows the object for which the RCS is to be determined, in this figure, a car. The second shows a theoretical scoop which captures energy and sends it to an isotropic antenna (i.e., an

antenna which emits an equal amount of energy in all directions). The size of this scoop can be changed to any required size. **The RCS of the object is equal to the size the scoop must be in order to induce the same level of return in the radar.** For example, suppose the car induces a 1 volt signal in the radar's receiver, and the scoop must be sized to 3 square meters to induce a similar 1 volt signal. Then the RCS for the car is 3 square meters (or 4.8 dBsm).

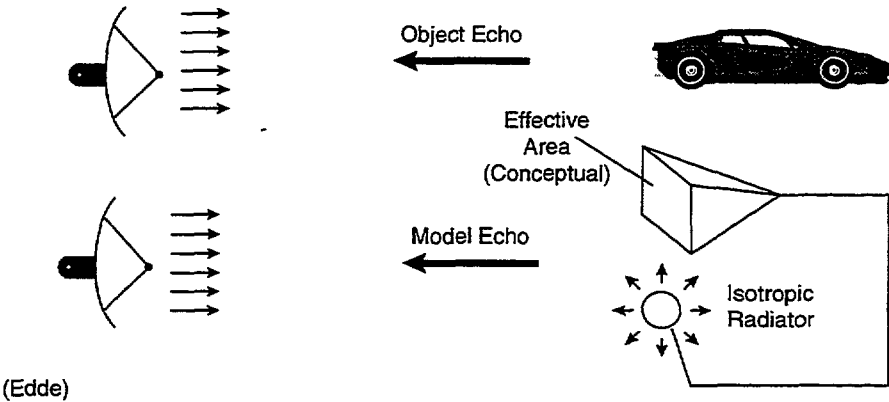


Figure A-5. Radar Cross Section Illustrated

In summary, it is a complex combination of reflection, refraction, absorption, transmission, and geometric directivity which defines how a particular object is viewed by a radar sensor. A parameter for measuring the “size” of an object from the radar’s perspective is called the radar cross section, which indicating how much energy will be reflected back to the radar.

A.4 FMCW RADAR OPERATING PRINCIPLES

FMCW radar operation follows the following basic principles:

- The transmit signal is frequency modulated (normally a linear modulation—chirp)
- The modulation of the received echo is compared to the modulation of the transmitted signal to determine time delay and therefore range
- Range rate is determined by range differentiation or Doppler processing

Graphical representations in both the time and frequency domains for a chirp waveform are provided in Figure A-6. The linear frequency modulation of a chirp is applied to the transmit frequency in an FMCW radar. In the case of the FLAR, the transmitted waveform is modulated over a 375 MHz bandwidth centered at 94 GHz.

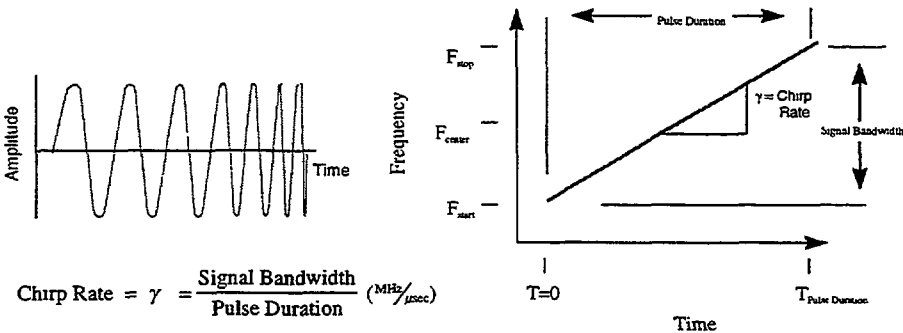


Figure A-6. Time and Frequency of a Chirp Waveform

The key to FMCW operation is that the shape of the waveform which returns to the radar after reflecting off objects is the same shape as the transmitted waveform. Figure A-7 illustrates how an FMCW radar can compare the transmitted and received signals to determine time delay.

The transmitted signal is emitted from the radar at time $T = 0$. Some time later (T_{d1}), a reflection back from an object is received by the radar. During the time of flight of the reflected signal, the transmitted signal frequency has increased as dictated by the chirp rate. Therefore, at any given instant of time after T_{d1} , there is a difference in frequency between the signal being transmitted and the one which was received. This frequency difference is proportional to the time of flight for the received signal (the proportionality constant is the chirp rate). Since radar energy travels through the atmosphere at a constant speed ($c = 3 \times 10^8$ meters/second), the time of flight is therefore proportional to the range to the object which reflected the energy (the proportionality constant is $c/2$). This is the principle by which an FMCW radar measures range.

Obviously, the radar can receive reflected signals from many objects at different ranges within its field of view. The physical means of comparing the transmitted and received signal frequencies is performed by a passive component called an RF Mixer. The transmit and received signal are input to this component, and the output is the difference between the two. The output of the mixer is referred to as the intermediate frequency or IF. **The plots of the “raw radar signal” provided in this report actually map the IF signal from the FLAR sensor.**

By capturing the IF signal from the FLAR and analyzing it with frequency domain processing techniques, an evaluation for how the radar is responding to its environment can be made.

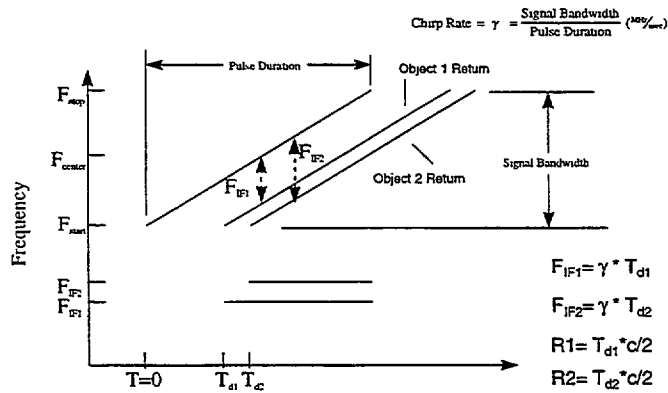


Figure A-7. Determining Time Delay